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The GEWEX Cloud System Study (GCSS)

GEWEX Cloud System Science Team

Internal Report No. 2

January 1993

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Report by GEWEX Cloud System Science Team*

Abstract

The World Climate Research Programme's Global Energy and Water Cycle Experiment (GEWEX) addresses both the hydrological and meteorological components of the water cycle. One of the biggest challenges in GEWEX is to improve the understanding of how the wide range of processes within clouds affects the atmosphere on the large scale and, thereby, to develop ways of parameterizing these processes within climate and NWP models. The Joint Scientific Committee of WCRP at its 1992 meeting approved the establishment of a GEWEX Cloud System Study as a long term programme that will address these issues mainly through the development of cloud resolving models and their use to generate realizations of a set of archetypal cloud systems. The focus of GCSS is on cloud systems spanning the mesoscale rather than on individual clouds. Observations from field programmes will be used to develop and validate the cloud resolving models which in turn will be used as test beds to develop the parameterizations for the large-scale models. The cloud resolving models provide synthetic data sets representing rather complete descriptions of entire cloud systems from which it will also be possible to develop algorithms for remote sensing observations.

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*Footnote: The Chairman of the GEWEX Cloud System Science Team, K.A.Browning was assisted in the preparation of this report by A Betts, P R Jonas, R Kershaw, M Manton, P J Mason, M Miller, M W Moncrieff, H Sundqvist, W K Tao and M Tiedtke (all of whom participated in workshop sessions held in Reading, UK, in 1991) and P V Hobbs, J Mitchell, E Raschke, R E Stewart and J Simpson (who contributed by correspondence). The GEWEX Cloud System Science Team has now been succeeded by a GEWEX Cloud System Science Panel charged with the implementation of GCSS. The corresponding author is Dr Keith A Browning, Joint Centre for Mesoscale Meteorology, University of Reading, Earley Gate 3, Reading, RG6 2AL, UK.

1. Introduction

Cloud systems on all scales play an important role in the global climate. Processes within cloud systems occur on scales too small to be represented explicitly in climate and numerical weather prediction (NWP) models. The effects of these sub-grid scale processes, therefore, have to be parameterized. Parameterization is the technique whereby the effects of unresolved processes are represented in terms of the primary dependent variables of a model.

GCSS is a programme intended to promote the description and understanding of key cloud system processes, with the aim of developing the necessary parameterizations for climate and NWP models. A physically based approach based on understanding rather than on empiricism is adopted so that appropriate parameterizations can be developed for the distinctive types of cloud system occurring in different regions of the globe. The description and understanding of cloud systems to be achieved in GCSS will also enable the development of improved algorithms for interpreting remote sensing observations of clouds and precipitation systems. Special field measurements are needed to make progress but these alone cannot be sufficient; there is a need also to exploit models, including cloud resolving models with domains large enough to span the scales being studied. The development of such models is central to GCSS. It is necessary to develop such studies in conjunction with theoretical models in order to minimise the empiricism and to reduce the inherent complexity of cloud-resolving models to a set of approximations judiciously expressed in mean flow terms. The specific ways in which observations and models will be used to develop parameterizations for large scale models are explained in later sections.

Progress in improving parameterizations of processes within cloud systems depends upon further advances in combined observational and modelling studies. Developments in technology are now making such advances possible. Computer power is becoming available to perform high resolution calculations in large domains. Remote sensing from space, ground and aircraft is providing high resolution observations of the convective and mesoscale phenomena associated with clouds, and improvements in four-dimensional data assimilation are enhancing our ability to optimize the use of incomplete observational data. The time is right to combine and systematically exploit these enabling technologies to address the problems of parameterizing the effects of cloud systems. The task is enormous but steady and even rapid progress is possible over the next decade, especially if parameterization is recognized as an intellectually challenging science in its own right rather than a pragmatic task.

Clouds have profound effects on the whole climate system, and international collaboration is needed to cover the full scope of the problem. GCSS is therefore established as a sub-programme of the Global Energy and Water Cycle Experiment (GEWEX) within the World Climate Research Programme (WCRP), to provide scientific leadership and an international planning framework to expedite such collaboration. To do this GCSS will provide a framework of scientific priorities and promote existing programmes that address those priorities. GCSS will also

promote ideas of outstanding promise, and identify gaps in capability and areas where additional effort is required. In such cases it will promote the development of key new facilities, such as specific airborne or spaceborne cloud measurements and a new generation of very high resolution numerical cloud system models. It will encourage not only the development of a hierarchy of numerical and theoretical models but also the integration of the results of the cloud system models with a comprehensive series of observational studies.

The observational requirements of GCSS will as far as possible be achieved through interaction with existing and planned field programmes in different regions. Some relevant field experiments and observing programmes, past and future, are listed in Table 1. Other more extensive data sets concerning clouds, such as those obtained in the International Satellite Cloud Climatology Project (ISCCP) are also vital.

Table 1. Past and future field experiments addressing cloud system problems (not exhaustive).

ALPEX	Alpine Experiment
AMEX	Australian Monsoon Experiment
AMTEX	Air Mass Transformation Experiment
ARM	Atmospheric Radiation Measurement
ASTEX	Atlantic Stratocumulus Transformation Experiment
ATEX	Atlantic Trade Wind Experiment
BASE	Beaufort and Arctic Storm Experiment
BOMEX	Barbados Oceanographic Meteorological Experiment
BOREAS	Boreal Ecosystems Atmosphere Study
CASP	Canadian Atlantic Storms Project
CLEOPATRA	Cloud Experiment Oberpfaffenhofen and Transports
COPT	Convection Profonde Tropicale
EMEX	Equatorial Mesoscale Experiment
EUCREX	European Cirrus Experiment
FIRE	First ISCCP Regional Experiment
FRONTS	a series of frontal observing programs mainly involving UK & France
GATE	(Global Atmospheric Research Program) Atlantic Tropical Experiment
GCIP	GEWEX Continental International Project
ICE	International Cirrus Experiment
JASIN	Joint Air Sea Interaction Experiment
KONTROL	Convection & Roll Vortices Experiment
KONTUR	Convection & Turbulence Experiment
MCTEX	Maritime Continent Thunderstorm Experiment
SMONEX	Summer Monsoon Experiment
STORM	Stormscale Operational and Research Meteorology
STREX	Storm Transfer & Response Experiment

TAMEX	Taiwan Area Mesoscale Experiment
TOGA COARE	TOGA Coupled Ocean Atmosphere Response Experiment
WAMFLEX	Wave and Momentum Flux Experiment
WMONEX	Winter Monsoon Experiment

The primary aim and objectives of GCSS are summarized in Table 2.

Table 2. Aim and objectives of GCSS

AIM: To improve the representation of cloud processes in climate and NWP models.

OBJECTIVES:

- To develop the scientific basis for the parameterization of cloud processes with due regard to physical and morphological identity among cloud system types.
- To co-ordinate the acquisition and assimilation of observations and the use of cloud-resolving models in the derivation of cloud system realizations for use in the development of parameterization schemes in large scale models.
- To promote the evaluation and intercomparison of parameterization schemes for cloud processes.

2. The importance of cloud systems to the large-scale circulation

Cloud systems have substantial effects on the dynamics of the large-scale circulation of the atmosphere. These effects arise from the modulating impact of cloud on the earth's radiation budget and from the thermodynamical consequences of phase changes in cloud. Moreover, precipitating cloud systems also have important effects on other sub-grid scale processes.

The radiative effects of cloud systems occur directly through the radiative properties of the clouds themselves, and indirectly, because they redistribute water vapour, the most important greenhouse gas. In a major study comparing 14 different global atmospheric models, Cess et al (1989)[1] show that the representation of the cloud-radiation interaction is the primary cause of differences in climate simulations. Indeed predictions of climate change are extremely sensitive to the way clouds are modelled. The big uncertainties come in partitioning total water in a climate model grid box between water vapour, precipitation, cloud water and cloud ice, and in specifying the horizontal and vertical extent of clouds as well as their microphysical properties. For example, one climate model predicts global mean warming due to doubling CO_2 varying

[1]Cess, R.D (1989): Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models, Science, 245, 513-516.

from 1.9K to 5.2K, depending upon the representation of cloud microphysics (Mitchell et al, 1989)[2]. Clearly, if prediction of global and, more particularly,regional climate change, is to be reliable, the effects of clouds need to be properly represented in climate models.

Many kinds of cloud systems have important radiative effects. In the tropics, deep convective systems transport water vapour and ice into the upper troposphere causing opposing effects through reflection and absorption of solar and infrared radiation, while boundary layer clouds reduce surface temperature by reflecting solar radiation. In middle latitudes, extensive cloud systems are associated with cyclonic storms, and in the middle and high latitudes, stratocumulus and stratus are common over cool moist surfaces, including regions of widespread oceanic upwelling.

Cloud systems also have important thermodynamical effects due to the phase changes of water, through condensation/evaporation, freezing and melting. The net release of latent heat from the precipitation processes is the major energy source which balances the net radiative cooling of the atmosphere. In the tropics, latent-heat release in convective clouds is a major energy source for many scales of motion, from squall lines, through hurricanes, to the Hadley-Walker and monsoon circulations. In many mid-latitude systems too, especially severe storms and explosively deepening depressions, latent-heat release is crucial. Numerical weather prediction and climate models need to represent these effects properly. It is particularly important that climate models should represent the large-scale features of the global circulation correctly, if we are to have confidence in predictions of regional climate change.

Turbulent transports and gravitational settling of hydrometeors within boundary layer clouds contribute to the redistribution of water and heat. Such processes have been little studied but it is known that the formation of drizzle in stratocumulus has a significant effect on the boundary layer water flux and consequently on the evolution of the cloud layer. Deep precipitating cloud systems, through evaporative downdrafts and forced mesoscale circulations, also have an important effect on surface and planetary boundary layer fluxes. This 'convectively disturbed' boundary layer has received little attention, yet it is an important part of the coupling of the atmosphere with terrestrial processes and with the ocean, both of which are fundamental to the climate problem.

Cloud systems affect the momentum balance of the atmosphere through direct momentum transport. This aspect has received little attention, but is known to be significant in organized systems. There are two related aspects, namely the internal redistribution of momentum, and the effect on surface wind stress curl that drives ocean circulations. The effect of gravity wave drag by orography is now a well known process in global models. A much less appreciated problem is the role of

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[2]Mitchell, J.F.B., Senior, C.A., & Ingram W.J. (1989); CO2 and climate: A missing feedback? Nature, 341, 132-134.

convectively generated gravity waves. Breaking gravity waves, generated in the troposphere and propagating upwards for great distances, couple the troposphere, stratosphere and mesosphere.

Cloud processes play a key role in coupling the atmospheric and oceanic circulations, especially in equatorial regions and high latitudes, through their influence on the radiative heating, surface fluxes and salinity budgets. The solar flux into the upper ocean is strongly modulated by cloud, and the net input of fresh water across the air-sea interface is affected by precipitation. The fluxes of heat, moisture and momentum control the coupling between the atmosphere and ocean, and coupled climate models are found to be very sensitive to the representation of those fluxes.

There are many deficiencies in existing parameterizations. Convection schemes use rudimentary cloud models, often lacking important cloud physics, such as the partitioning of water and ice. There is little or no account taken of the crucial role of vertical wind shear in determining cloud structures and transports. There are uncertainties over the coupling of the parameterization scheme to the resolved scale. The interactions of convective clouds with radiation and the sub-cloud layer are major problem areas. These should all be strongly linked, but at present they are usually independently parameterized. Similar deficiencies exist with layer cloud parameterizations. These inadequacies degrade model performance on all time scales: improved parameterizations should lead to reductions in the systematic errors in both climate and weather prediction models.

A complicating factor which must be taken into account is the geographical variety of cloud phenomena and their organization. Present parameterizations do not recognize this variety or the consequent variability of cloud processes. Some types of cloud systems are statistically homogeneous to a first approximation, while others are organized, especially on scales 0(10-100 km). However, most current parameterization schemes assume that all systems are homogeneous. Although this assumption is reasonable for some systems, the parameterization of even these systems is still not adequate. For organized convection this assumption is clearly wrong and parameterizing the effects of such systems is a particularly important area of research. Because of the non-linearity of many atmospheric processes, the inferred effects of cloud systems may be in error even if they are calculated using accurate representations of the mean cloud properties. For example, radiative effects of clouds cannot be represented correctly using a grid volume mean value of the liquid water content.

The grid spacing of climate models over the coming decade may come down to 50 km, enabling them to resolve scales of about 200 km. Cloud systems are generally organized by the large-scale flow, and they tend to have scales comparable with or in some cases greater than the resolution of the climate models. Moreover, cloud systems have lifecycles with timescales greater than the time step of the models. It follows that an understanding of the interactions of processes occurring on different scales will be a major issue for the parameterization of the effects of cloud systems in these models. The reduction in model grid spacing will

enable cloud systems to be represented explicitly but it will still be necessary to parameterize the effects of individual clouds within the systems.

Parameterizations need to be developed for cloud systems on a range of scales. The cloud systems involve coupled dynamics, thermodynamics and physics extending from turbulent surface fluxes to radiative transfer. The development of improved parameterizations will be crucially dependent upon improvement in understanding of these physical processes, rather than upon the search for purely statistical relationships between variables. The need to improve understanding of processes results from the need to ensure that parameterizations, by being physically based, are sufficiently robust to be used under a wide range of conditions. The more empiricism can be reduced in parameterizations, the more likely they are to be reliable as external conditions change.

Improvements in the representation of cloud systems will benefit not only climate models but also numerical weather prediction analysis and prediction systems. The improvements should lead to better data assimilation systems, which are being used to provide homogeneous and consistent global climate analyses. Data assimilation for climate observations will become increasingly important as new data types appear from the next generation of satellite and ground-based remote sensing instruments. Improved understanding of cloud processes will also lead to more appropriate algorithms for interpreting remotely-sensed observations of cloud systems, including retrieval of their microphysical properties.

3. Cloud processes needing to be parameterized

A wide range of cloud system processes needs to be parameterized. The following is a list of the most important of these processes. Cloud radiation interactions have traditionally been regarded as the most important processes; however, the importance of other processes should not be underestimated. Indeed cloud systems generally involve such strong interactions that correct parameterization of one aspect depends on a correct overall description. For example, prediction of details of the drop size distribution is crucial to correct representation of radiative transfer and of precipitation flux of water; an adequate representation of glaciation is also crucial to both processes.

(i) Cloud-radiation interaction

Water vapour, as the main greenhouse gas in the atmosphere, provides a major positive feedback in the climate system. The global distribution and cycling of water vapour is not well known at present. It is very dependent upon the action of clouds, but the nature of this dependence is poorly understood.

The radiative properties of the cloud systems themselves are strongly dependent upon their structure. A cloud system parameterization must therefore specify both the horizontal cloud cover and vertical distribution of cloud in a grid box. The kind of problems to be addressed include, for

example, the effects of an extensive cirrus anvil above a convective cloud system, the transition of cloud type across a cold front, and the transition from a solid overcast to broken stratocumulus. There are two distinct issues. The first is how these cloud properties are determined by the large scale conditions. The second is how different distributions of cloud cover and type affect the radiative transfer. It is the first of these two problems that is the major stumbling block and where the greater effort needs to be directed.

Theoretical, numerical and observational results suggest that, in addition to their gross horizontal and vertical characteristics, the microphysical properties of clouds (particle number, size and phase) have a significant effect upon climate. Aerosols are also important in so far as they influence the microphysical properties of the cloud: they may influence not only their radiative properties directly but also their persistence. Further field observations and model development are required to determine the dominant cloud properties that need to be represented in parameterizations.

(ii) Transport of heat, moisture, momentum and chemical species

A primary effect of cloud, particularly convective cloud systems, is on the distribution of heat, moisture and momentum in the atmosphere. Thus the vertical structure of temperature, humidity and velocity in a climate model is strongly coupled to the parameterization of processes within cloud systems. Transport of trace chemical species is also an important issue for climate studies. While the horizontal transport of inert species by the resolved flow is now being implemented, scant attention is being given to the vertical and slantwise transport, and to the problem of aqueous chemistry. A key parameterization task, then, is to specify the various processes that contribute to these transports. While current parameterizations account for the bulk transport of heat and moisture, the representation of momentum transport is generally very poor. This is a particularly pertinent problem for organized convective systems in which it is known that the momentum flux is anisotropic, with upgradient and downgradient transport in orthogonal directions. This problem is just beginning to be addressed.

(iii) Precipitation

The spatial and temporal distribution of precipitation is strongly influenced by mesoscale dynamical processes. It is important for the purposes of surface hydrology to be able to infer the intensity and scale of precipitation events within large scale model grid squares. This depends on the convective and mesoscale circulations within the grid, and on the topographic effects (see (v)), as well as on the microphysical processes of precipitation.

(iv) Interactions between surface fluxes and clouds

Many cloud systems, such as low-level stratus cloud and convective clouds, depend critically upon surface fluxes which are themselves modified

by the cloud systems. For example, the cold downdraughts of convective systems strongly modify surface fluxes, and radiative interactions with stratus lead to a stable layer at cloud base which inhibits surface fluxes. Proper treatment of these interactions must be incorporated into parameterizations.

Interactions at the air-sea interface are important over a range of time scales, extending from less than a day in cases of rapid cyclogenesis (eg the development of intense cyclones on the eastern coast of USA and Australia) to seasonal and longer variations where the thermal inertia of the oceans provides a base for climate prediction. The increasing success of the WCRP Tropical Oceans-Global Atmosphere (TOGA) program arises from improvements in our understanding of air-sea interactions, and the TOGA Coupled Ocean-Atmosphere Response Experiment (COARE) is being conducted in the tropical western Pacific during November 1992 to March 1993 to focus particularly on these processes.

(v) Topographic effects

Surface topography often plays a significant role in the initiation, structure and evolution of cloud systems. The enhancement of precipitation by orography is generally not well represented in the sub-grid scale components of climate models. Similarly the generation and modification of stratus layers at low and middle levels and cirrus at high levels by orographic forcing are poorly represented since they depend on vertical, topographically induced, motion on a scale much smaller than the model grid scales. Topographic gradients also influence the initiation processes for convective cloud systems.

(vi) Interaction with the lower stratosphere

At low latitudes deep convection is the primary mechanism for the transport of mass and momentum into the lower stratosphere. The characteristics of the upper troposphere and lower stratosphere are greatly affected by the action of deep convection, both slantwise and vertical. The exchange of mass across the tropopause is critical to the determination of the distribution of trace gases, such as ozone and nitrous oxide, that have an impact on climate. Intrusion of stratospheric air may alter the concentration of cloud condensation nuclei in the upper troposphere which may affect cirrus ice crystal concentrations and size spectra.

(vii) Interactions between clouds at different altitudes

High-level clouds affect low-level clouds via radiative interactions and through the seeder-feeder mechanism of precipitation development. For example, crystals falling from higher level clouds, or which remain after the evaporation of these clouds, may induce glaciation in lower level clouds at comparatively high temperatures.

The above processes are summarized in Table 3.

Table 3. Summary of processes to be parameterized

(i) Cloud-radiation interaction
- effects of clouds on water vapour distribution
- horizontal extent of cloud
- vertical extent of cloud
- cloud microphysics

(ii) Transport of heat, moisture and momentum
- impact on profiles of T, q and V

(iii) Precipitation
- microphysics
- intensity and scale of surface precipitation events

(iv) Interaction with surface fluxes
- shadowing
- fresh water flux
- impact on boundary layer profiles

(v) Topographic effects
- precipitation enhancement by orography
- modification & enhancement of stratus and cirrus
- initiation of convection

(vi) Interaction with lower stratosphere
- transport of trace gases through tropopause

(vii) Cloud-cloud interactions
- cloud structure and lifetime
- cloud microphysics
- cloud radiation interaction

4. Cloud system classification

Cloud processes interact over a wide range of scales, from microphysical and turbulent scales of much less than 0 (1 km), through convective clouds on scales 0 (1-10) km, mesoscale convective systems on scales 0 (100 km), to frontal systems and cloud clusters up to 0 (1000 km). The task of describing and understanding these processes and their role in the large scale circulation of the atmosphere is a major scientific challenge.

It is customary in current convective parameterization schemes to identify only three principal cloud types, namely upright, slantwise and stratiform convection and this simple classification has considerable utility. However, a physically more detailed classification is appropriate to GCSS because the fluxes (turbulent, radiative and convective) are fundamentally affected by synoptic conditions through their effect on turbulence, convective elements, collective (ensemble) behaviour and

overall physical characteristics. These considerations are not treated in current parameterization schemes. The importance of structural aspects means that the primary concern in GCSS is with cloud systems as distinct from individual cloud types. Basis research is essential to quantify the physics and transport properties of each class in order to lead to new parameterization approaches that allow for the inherent diversity of cloud system behaviour. Several major classes are identified: boundary layer stratus and stratocumulus, cirrus, cold air convection and ordinary cumulonimbus, mesoscale convective systems, frontal clouds and orographic clouds.

5. Methods for developing parameterizations

A number of numerical and analytical methods are used in the development of cloud parameterizations. These methods are used to ensure that parameterizations are scientifically sound and consistent with observations. Modern data assimilation methods (Section 7.3) are expected to play an increasingly important role in making optimal use of relevant data for the development and validation of parameterizations.

5.1 The use of weather forecast models and climate models

A direct approach to improving cloud system parameterizations in large scale models is via the diagnosis of systematic errors in the weather forecast and climate models. In weather forecast models the diagnosis of errors may be achieved through the analysis of initial tendencies after the assimilation of data. In climate models it can be achieved by comparisons with observational data concerning the general climate and in particular with comparisons concerning the statistics of cloud systems. However, while such studies may highlight aspects in which the combined parameterizations are deficient, they seldom provide an adequate scientific basis for improving individual parameterizations.

The scope for this approach depends critically on the accuracy and density of synoptic observations and the availability of climate data concerning cloud systems. In the latter respect the proposed long term monitoring in the Atmospheric Radiation Measurement (ARM) Programme and the Earth Radiation Budget Experiment (ERBE) data sets are unique.

The studies undertaken with this approach will continue to be important in highlighting problems in large scale models and will remain an essential test of model performance. It must be noted, however, that the errors diagnosed are net errors that arise from the sum of observational errors and the various errors inherent in the model and therefore may be model dependent.

5.2 Observational budget studies

Budget studies enable one to infer the source and transport terms associated with unresolved cloud processes, rather than measure directly the details of the

physical processes. Historically this has been achieved by the analysis of networks of radiosonde soundings launched at frequent intervals, using a residual technique. In the future, networks of wind profilers and other continuously measuring instruments are expected to reduce the observational and statistical sampling errors. When dealing with the coupled ocean-atmosphere, budgets should be derived used oceanic (surface and sub-surface) measurements in addition to the atmospheric measurements.

The budgets derived directly from time synchronous data provide a check on the validity of a parameterization scheme and, in the past, the diagnostic interpretation of these budgets has been one of the best methods for improving parameterizations, particularly of convective transports. Unfortunately conventional budget calculations do not provide datasets that are dynamically consistent. Also the input (of observations) and output (of analyzed variables) are incomplete. This has significantly reduced their usefulness for parameterization studies. We are now moving into an era where four dimensional data assimilation becomes feasible, from the cloud to the synoptic scale, using a range of dynamical models. Therefore budget products can be derived directly from the model assimilation, although these products necessarily depend to some degree on the physical parameterizations used in the model. Of particular concern is the current lack of availability of improved data sets (spatial and temporal) to establish comprehensive budgets. The GATE data set continues to be the best available on scales of motion of order 100 to 1000 km. There is a need to alleviate this situation and include remote sensing data such as those from the new profiler technology.

Budget studies involve area and ensemble averages, and their interpretation becomes difficult when there is no clear scale separation; that is when the unresolved phenomena, such as squall lines, have a scale comparable with the resolved scale of the measurements. In the circumstances a case study budget, as opposed to a statistically-based budget, becomes appropriate.

5.3 Detailed observational case studies

In detailed observational case studies the budget is supplemented by various measurements of the details of the processes involved. Such observations are necessary for extending parameterizations from the empirical approaches of the preceding methods to a theoretical or conceptual model basis. Only when it has such a basis will it be possible to extend the parameterization to regions and/or situations that have not been studied observationally. These detailed observational studies are essential to ensure that all relevant processes are being addressed and that the net effects are attributed to the right cause. They are of special importance to the study of organized systems for which a simple statistical description is clearly inadequate.

Modern developments in remote sensing still fail to provide the spatial resolution and detail necessary for a full description of all processes. The partial descriptions achievable using modern techniques are, nevertheless, vital to reveal details of processes. For example, remotely sensed column liquid water content

can provide a useful constraint in the modelling of cloud entrainment processes and in understanding the distribution of the latent heat source. There is also a research opportunity to use cloud resolving models to assimilate these detailed observations in order to improve the value and integrity of the results.

5.4 Cloud scale model simulations

The term cloud scale (or cloud resolving) model is used for a three-dimensional numerical model capable of describing motions and processes within the cloud systems. Depending on the type of cloud system involved, the spatial resolution might vary between 0(1 km) and 0(100 m). Such models are capable of giving an accurate description of the flow dynamics. Explicit representation of precipitation size distribution and physics is also possible in some limited applications but generally they still require parameterizations of cloud physics, radiative transfer and turbulence. However, from the demonstrated performance and experience with existing models of this type, it is clear that the parameterizations needed for cloud scale models, though a major challenge, may be easier to achieve than those for climate models. The parameterizations in large scale models have to deal with the ensemble properties of the whole, rather heterogeneous system whilst the parameterizations in the small scale cloud model deal with more statistically homogeneous behaviour. The cloud scale model parameterizations link to local observations of cloud systems and not to the net properties of the whole complex system.

With further development of these models, there will be an opportunity to provide the detailed and comprehensive descriptions of cloud systems that are needed to advance parameterizations and which it is not feasible to obtain by means of purely observational approaches, for example detailed flux profiles and their evolution. The cloud scale models have the potential to provide detailed simulations of a wide range of cloud systems. They also allow experiments to be performed to give insight into how the final parameterizations in large scale models should depend on the various factors. Noting the limitations of the other available approaches, the use of cloud scale models is a long term strategy which lies at the heart of the GCSS approach.

One aspect of the use of cloud scale models concerns the need to understand the role of organized cloud systems and the interactions between cloud resolving scales and larger scales. Such interactions raise special difficulties for parameterizations that are intended to represent average effects rather than individual events. By using either mesoscale models with resolutions of order 10 km or cloud scale models nested within larger scale models, there is an opportunity to provide understanding of these phenomena and new methods for representing their fluxes in large-scale terms.

5.5 Development of theoretical concepts

To progress from either direct observations or cloud resolving model data to the development of improved parameterizations, it is necessary to derive an appropriate theoretical or conceptual base. Simplified realisations based on theoretical formulations must be produced to understand scale interactions and improve parameterizations schemes. This could include the derivation of flux laws from dynamical models and the extension of current, or the definition of new, closure methods. This approach would introduce dynamical models into parameterization research and hence improve the cloud models currently used in schemes. These new formulations will need to be validated against fine-scale models and observational data.

6. Development of parameterizations within future programmes

6.1 Direct development of parameterizations from observations

Figure 1 illustrates the steps in the direct development of cloud parameterizations in climate models. The term 'direct' is used in the sense that the development is not accomplished via the use of cloud resolving models. The direct method is that used by the large scale modelling community epitomised by WGNE (the Working Group on Numerical Experimentation). The longer term strategic approach to be used within GCSS is described in Section 6.2.

The identification of the need for an improved parameterization of a particular process is determined by consideration of the systematic errors in the model climate or by consideration of the local errors that can be monitored in numerical weather predication models. Improvement of the parameterization of a particular process is then justified if the model shows a sensitivity to that parameterization. Care is needed, however, in the interpretation of sensitivity studies because of inadequacies in a model may mask or exaggerate the actual sensitivity of climate to a particular process.

Although global or large-scale observations can be used to identify systematic errors in a model, specialised field experiments are generally needed to provide information about the dependence of a process on the relevant scales of interaction. The analysis of field observations can be carried out on three levels: diagnosis, objective analysis, and data assimilation.

The diagnosis of the bulk effects of cloud systems directly as a residual from field data is the most common method of estimating the apparent sources of heat, moisture and momentum (Q_1, Q_2 & Q_3). This technique does not, however, ensure that the diabatic forcing terms are dynamically or thermodynamically consistent, and the results usually have some error, sometimes systematic error, owing to uncertainties in the field data.

Objective analysis techniques can be used to diagnose the effects of cloud systems on the atmosphere in the region of a field experiment. Such methods account for the non-uniformity of and error in raw data, and they can provide some constraint on the relationship between variables. As explained in Section 7.3, the analysis of observations can be improved by using 4-dimensional data assimilation, thereby combining the consistency of model-derived fields with the lack of bias often associated with such fields.

Before parameterization is tested in a 3-D climate model, it is desirable to determine its behaviour in a stand-alone 1-D model, ie., a 1-D version of the full 3-D climate model. The tests with a 1-D model on data sets from specific field experiments, such as GATE, allow the local impact of the parameterization to be determined in controlled conditions of external forcing. Once the parameterization is found to yield satisfactory local behaviour in the 1-D model, it can be implemented in the full climate model so that its free interaction with the large-scale dynamics can be examined.

6.2 Development of parameterizations from observations plus cloud resolving models

Figure 2 shows the two-stage methodology by which field observations can be combined with simulations using cloud resolving models to develop parameterizations of cloud and precipitation processes for use in global scale models. The first stage, to develop and validate the cloud resolving model with the help of observational field experiments, is clarified in Figure 3(a). The second stage, to use the cloud resolving model to develop the parameterizations for large scale models, is clarified in Figure 3(b). This approach, using cloud-resolving models, is the essential focus of GCSS.

Final observations are used in two ways (see Figure 3(a)). First they provide information that will be used to verify specific hypotheses concerning the physical processes involved; the design of individual field experiments will need to be determined by the hypotheses to be verified. Secondly, the field observations will be used to verify the simulations obtained using cloud resolving models for a variety of different cloud system types. These verification studies will be used to identify sensitivities and aspects of the cloud resolving models requiring improved parameterization of small scale physical processes. The response of cloud resolving models to improved parameterizations of small scale processes will then be determined and this information fed back into the development of the small scale parameterizations. This procedure will lead to the overall improvement in the parameterizations in the cloud resolving models, although, owing to interactions between parameterized processes, improvements in one area may highlight deficiencies in another. As these refinements progress, results from the cloud scale models will become available as tools for the development of parameterizations for global scale models.

The range of conditions and cloud types that may be covered by field experiments is obviously limited. However, the cloud resolving models, developed

as indicated above, can be run to provide detailed and consistent synthetic data sets for the full range of cloud system types. Diagnostics from the simulations will be used to improve understanding of the physical processes on the cloud scale, especially those involving interaction between dynamical and microphysical processes that are not easy to observe directly. Improved understanding of the critical processes will be used as the basis of simplified one dimensional process models which will be further developed to form parameterizations for large scale models. Additional input to the development of the one dimensional process models will come from theoretical and dynamical models, also aimed at understanding the basic mechanisms but from a different viewpoint.

The construction of a set of cloud system realizations is an important part of the GCSS strategy not only for parameterization development; these realizations will also be available for use in the development of remote sensing algorithms (see Section 8).

7. Data requirements for development and validation of parameterizations

7.1 General data requirements

A dominant and pervasive feature of the physical processes in cloud systems is the interaction between scales, which span the synoptic down to the microscale. Systematic field observations are needed across these scales in order to develop and validate cloud parameterizations. Moreover fine-scale cloud models must be verified at all relevant scales, and then they can be used to provide comprehensive estimates of the small-scale structure of cloud systems. Table 4 summarizes the range of data needed for cloud system studies.

Table 4. Data requirements from observations (supplemented by model output)

- Large-scale forcing on grid scale
  - profiles of temperature, moisture, momentum and vorticity
  - convergence of mass, heat, moisture and momentum
- Apparent sources of heat, water and momentum over grid scale
  - profiles of Q_1, Q_2 and Q_3 (heat, moisture and momentum sources)
  - surface fluxes of heat, water (including precipitation), momentum and radiation; also need distribution of surface properties, eg. soil moisture and vegetation type
  - radiative flux at top of atmosphere
  - precipitation/condensation profile
- Distribution of cloud properties in grid volume
  - cloud cover distribution
  - vertical cloud distribution
  - cloud type distribution
  - radiative flux profile

- o Distribution of internal properties
  - mesoscale circulation and pressure field
  - updraught and downdraught areas
  - mass fluxes
  - microphysics, including size distribution, CCN, IN and haze

The main purpose of cloud parameterization is to approximate the apparent sources of heat, moisture and momentum due to sub-grid scale cloud processes. These features can be validated by bulk budget studies over the grid scale, and so it is important that data sets of mesoscale cloud properties include information on the bulk diagnostic budgets of heat, moisture and momentum.

The radiation budget in a grid volume is particularly sensitive to the distribution of the water phases over the volume. Data on these distributions are therefore needed for cloud parameterizations. Modern developments in airborne instrumentation, combined with new techniques for data analysis, offer the possibility of determining water and ice content to a high accuracy. More detailed information on the internal structure of cloud clusters and even individual clouds is also required to develop parameterizations. In order to model the structure of organized convection, it is necessary to have data on the mesoscale circulation (including the pressure field) of cloud systems.

Satellite-derived cloud properties are crucially important. Some of the necessary measurements exist but require further development of retrieval algorithms. These relate to cloud cover, cloud water content, effective cloud droplet radius and precipitation intensity. Currently available satellite data are essentially 2-dimensional (vertical integrals or averages) although there is potential for inferring a limited degree of vertical information. Vertically resolved cloud measurements are so important to the vertical distribution of cloud-induced radiative heating, and to the effect of clouds on the surface radiation budget, that there is an urgent requirement for greatly improved measurements of cloud vertical structure. The most promising approach during the coming decade is offered by space borne millimetre wavelength radar.

The generation of comprehensive cloud-system data sets from field observations will require coordinated measurements across a range of in situ and remote platforms. It is important that future field projects, aimed primarily at one scale of cloud systems, should attempt to obtain relevant data across the range of interacting scales, in order to optimize the scientific returns on the overall investment in the collection of the data set. For example, studies of mesoscale frontal structures should include observations of large scale dynamical forcing as well as observations of the bulk properties of clouds within the system.

7.2 Additional observational requirements for development of parameterizations in cloud resolving models

The development of cloud resolving models will require parameterizations of the microphysical processes. In order to develop such parameterizations, detailed

measurements will be needed both to assist with the testing of scientific ideas and to assist with verification of models making use of the parameterizations. The specialised requirements mentioned below are in addition to much of the data listed above in Table 4.

Development of microphysical parameterizations requires information on droplet, ice crystal and aerosol spectra with resolution of 0(10 m). In addition, it is necessary to obtain detailed information on the evolution of the water and dynamical fields with a resolution of 0 (10 min) for layer clouds and even better for convective clouds. The microphysical processes can be prohibitively complex, especially if coupled to radiative processes and if spectral distributions are used. It will be necessary to obtain a minimal but realistic specification of microphysical complexity.

Parameterization of the turbulent fluxes within the clouds requires high resolution, three dimensional, velocity measurements as well as temperature and water fields with comparable resolution. While, for most purposes, measurements at a few instants during the lifetime of a cloud system will be adequate, it would be desirable to obtain the evolution of such fields throughout the life cycle of some cloud systems. Such observations are within the capability of current airborne and surface based instrumentation.

The parameterization of microphysical/radiative interactions requires, in addition to high resolution microphysical data, broad and narrow band radiative flux measurements within, above, and below cloud. Sampling of cloud water for chemical and aerosol analysis is also necessary.

These data requirements can be met only with a combination of multi-level aircraft measures, airborne and ground based radars (multi-wavelength Doppler and polarisation diversity) combined with high resolution, multi-channel (visible, IR and microwave) satellite radiometers. The data will be required for a range of cloud system types formed under a variety of conditions, to establish the generality of such parameterizations. While the requirements are extensive, some aspects of parameterization development may be met individually, by focused experiments.

7.3 Four dimensional data assimilation (FDDA)

As noted above, the use of numerical models to assimilate observational data provides an effective way of generating dynamically consistent datasets and hence of making optimal use of the observations in a variety of circumstances. Data assimilation of this type is now performed routinely at various numerical forecast centres producing global datasets. The development of improved four-dimensional data assimilation techniques in conjunction with advanced mesoscale models holds special promise but has yet to be implemented. Another development is the adjoint technique that is beginning to be seriously considered for the mesoscale data assimilation. Of particular importance will be the incorporation into mesoscale models of remotely sensed data, such as several types of profilers, integrated sounding systems,radio-acoustic sounders, lidars and an extended use of routine

data from commercial aircraft. It will also be important, but difficult, to extend these techniques to cloud scale models. The aim would be to embrace the retrieval of microphysical parameters from cloud radars, lidars and microwave radiometers as well as the assimilation of special aircraft measurements from field experiments in which flights through the cloud system are necessarily made at only a few points in space and time.

Satellite cloud data sets are especially valuable for assimilation. The recently revived approach of dynamical initialization for numerical models, now with the aid of digital filtering, is particularly promising in this regard. The dynamical type of initialization implies that the full model equations are integrated. Hence all dependent variables become adjusted to the momentary state of atmospheric motion, for example even cloud water and precipitation, assuming they are carried as dependent variables. Assimilation of moisture information is a critical research topic in FDDA. A specific interest is in specifying the latent heating at the initial forecast time because a "spin-up" problem can occur in the earlier stage of forecasts. The spin-up is caused both by deficiencies in the specification of vertical velocity and humidity in the initial conditions and by inadequacies in physical parameterizations of prediction models (eg. cumulus parameterization). The GCSS aim is to improve the representation of cloud processes in climate and NWP models. Thus, GCSS would help FDDA by developing a better representation of moist processes in NWP models.

Data assimilation has distinct advantages over other methods of data analysis. Besides ensuring physical consistency between the dependent variables, it integrates data from various observing components, it allows for inhomogeneity of the observational data in space and time and (in combination with variational techniques) additional data such as precipitation rate and radiative fluxes can be assimilated. The limitation of this method is that the final data set is to some extent affected by the imperfection of the model. It must be stressed that 4-D data assimilation is a major undertaking requiring large resources (scientific and computing) and coordination is essential if it is to be successful.

8. Use of cloud system studies to improve retrieval algorithms

As part of the programme of development of parameterizations of larger scale processes, cloud resolving models will be used to develop a series of realizations of different cloud systems which will include rainfall and water/ice distributions throughout the cloud system lifetime. These realizations will also be used to develop algorithms for the retrieval of remotely sensed cloud properties; the development of such algorithms is essential if the full range of data requirements is to be met.

The cloud system realizations will be used as the basis of models to calculate the upwelling radiance at different wavelengths. Presently available results, based on observed fields, are limited to a small number of situations whose generality is not known. Moreover, the observations seldom form a complete set, for example covering only part of a cloud system's lifetime. Synthetic data sets from model

simulations are currently available for only a few cloud systems; the problem of generality remains while the results are also sensitive to microphysical parameterization schemes.

One of the most significant improvements in remote sensing technology involves rain retrieval using various frequencies of passive microwave channels. Passive microwave rain retrieval algorithms have been developed in different institutions. The majority of these algorithms require the use of radiative transfer models, but the vertical structure of the cloud parameters (hydrometeors) is the driver in the radiative transfer calculations that determine upwelling radiance at the top of the atmosphere. Since there are no direct measurements of these vertical profiles, a cloud resolving model is needed to provide the cloud profiles associated with the different types of cloud systems. One product is a relationship between rain rate and brightness temperature which can be used to *retrieve* rain rates from brightness temperatures sensed by air- or space-borne microwave instruments, and then tested by comparison with other rain rate observations, obtained for example by calibrated surface radars.

The use of satellite-borne radar to monitor rainfall is a central part of the GEWEX but even ground based radar measurements are presently subject to large uncertainties. The cloud system realizations developed within GCSS will be used to develop improved adjustment factors for use with different cloud system types, for example, to include the effects of sub-sampled volume variability or the impact of different forms of the droplet size distribution for different cloud system types. They will also be used to model the performance of proposed new techniques and to determine the accuracy to be expected under a variety of conditions by enabling a comparison to be made between simulated retrievals and the exact (model based) local values.

9. Activities to be promoted under GCSS

The main tasks under GCSS can be summarized as follows:

- To identify key questions about cloud systems relating to the parameterization problem and specify approaches to address them.

- To derive the simplest possible archetypal classification scheme for cloud system regimes and to determine the large scale factors responsible for regime selection.

- To specify and instigate the acquisition, analysis and application of data sets suitable for the development and validation of cloud parameterization schemes in climate models;

  (a) regional data sets for a set of archetypal cloud systems and;
  (b) global data sets with which to generalise the results from regional studies.

- To promote the development of a hierarchy of cloud system models, including mesoscale models, cloud resolving models and idealized models, and their use in the development of parameterization schemes.

- To organize intercomparisons and diagnostic studies relevant to cloud parameterization.

A GEWEX Cloud System Science Panel has now been formally established as part of the WRCP structure alongside panels dealing with radiation (Working Group on Radiative Fluxes) and hydrology (GEWEX Continental International Project). The GCSS Panel has begun to prepare a detailed implementation plan. Further information about GCSS will be promulgated through WCRP channels and at scientific conferences as the details of the plan become more clearly formulated. GCSS is a long term strategic approach to a difficult and complex problem. To be realistic, field experiments, model development and theoretical studies will need to continue over a time scale of decades.

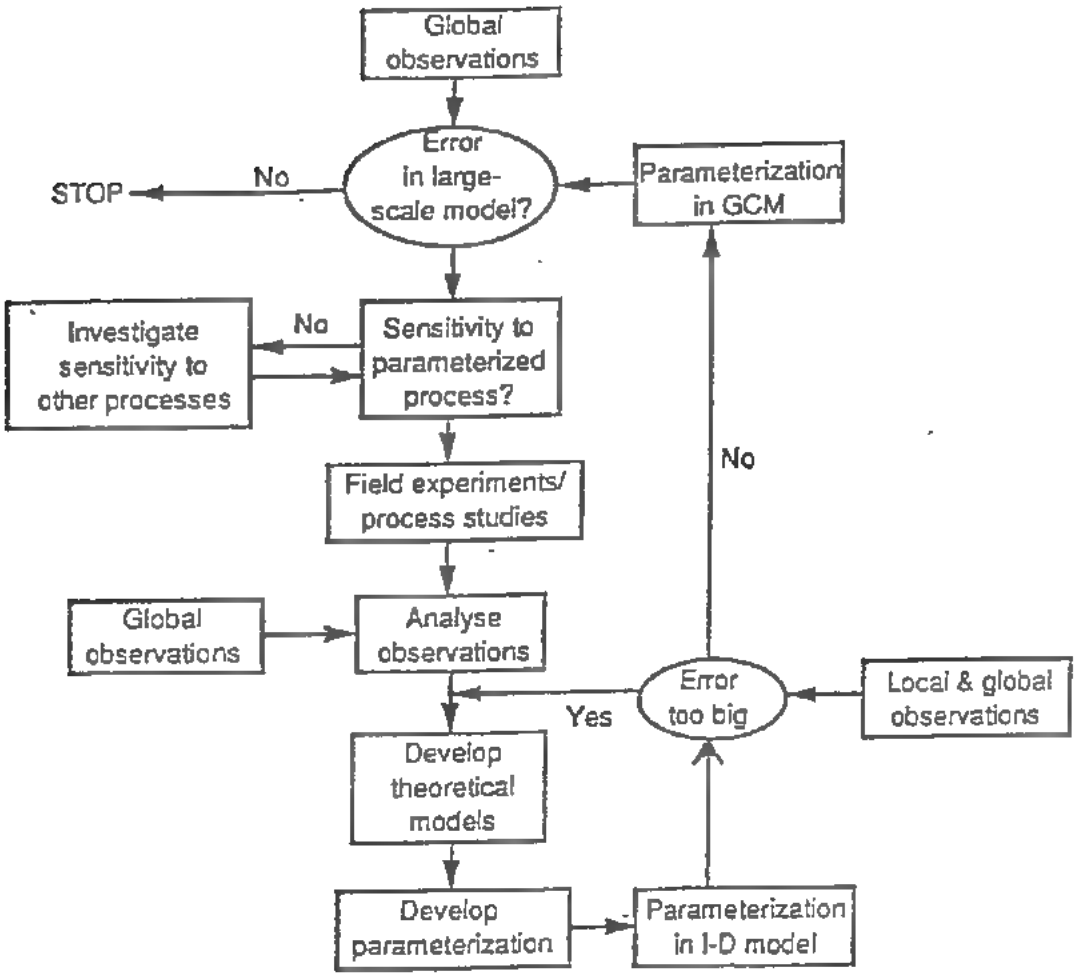

Fig.1. Flow chart for direct development of parameterization

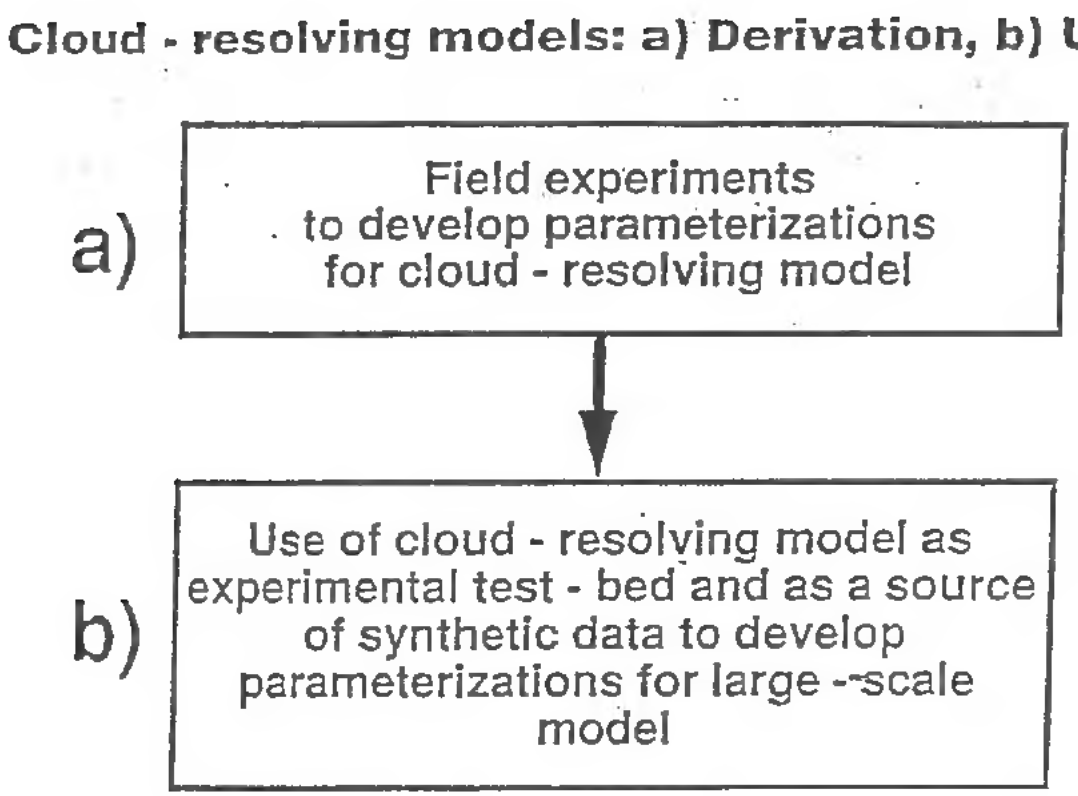

Fig.2 (see legend over page)

Fig.3 a) Derivation of cloud - resolving model

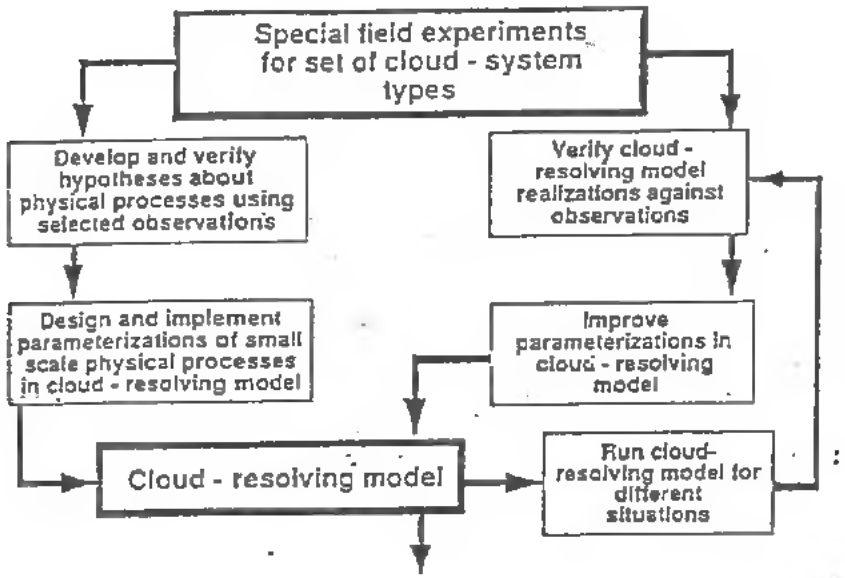

Fig.3 b) Use of cloud - resolving model to develop parameterizations in large scale model

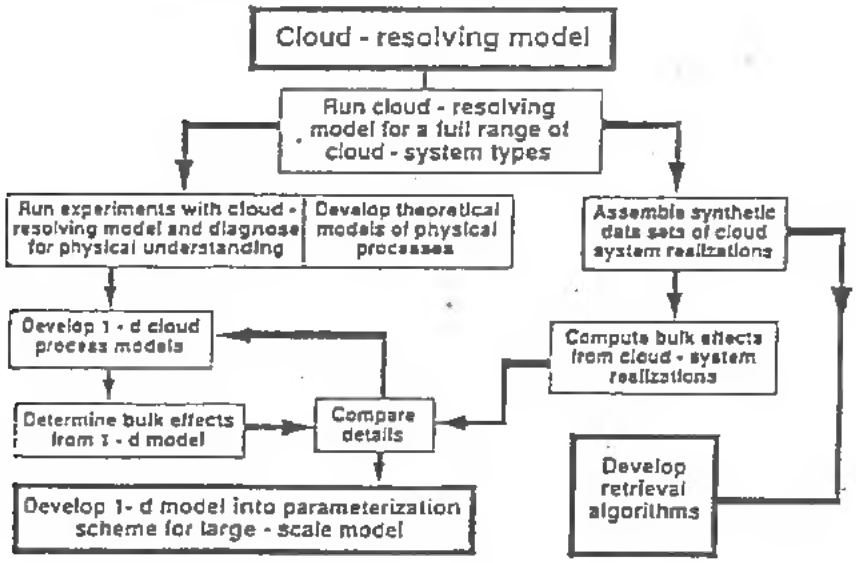

Fig 2 and 3. Flow charts showing how field observations and simulations using cloud resolving models may be combined for the purpose of improving parameterizations in large scale models.

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1. **Research Strategy and Programme.**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS).**
   GEWEX Cloud System Science Team
   January 1993

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